Spring 2021

MEMS 411: The Jolley Trolley

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SP21 MEMS 411 Mechanical Engineering Design Project

Jolley Trolley

Since the advent of architecture, cranes have been an essential tool in moving and placing heavy loads. Even in modern times, cranes of all sorts are still being used. This project focuses on the design, fabrication, and testing of a small scale model of an overhead gantry crane to be used by our customer, Dr. Jackson Potter, as a classroom demonstration of the engineering techniques used to control a real crane. The result of this design process was The Jolley Trolley, a portable gantry crane made from extruded aluminum and 3D printed PLA, controlled with an Arduino Leonardo microcontroller, and actuated with a stepper motor. The device was designed to be able to fold up for easy storage during transport, and was tested according to three main performance goals. First, the trolley needed to be able to move faster than 1ft/s in order to be clearly visible. A maximum speed of 0.933ft/s was achieved during testing, meaning that the device almost reached its goal but more iteration would be needed in future versions to reach the desired speed. Second, the trolley needed to have "soft stops" implemented, such that it could stop when it was at the edge to avoid breaking itself. This was done using hall effect sensors mounted on either side of the track and magnets mounted on either side of the trolley, and was tested successfully many times. Finally, the device needed to weight less than 10 lbs for ease of transport. The final prototype weighed in at approximately 9.8lbs, meaning that this goal was also met.
The current version of the Jolley Trolley is serviceable for use in a classroom setting, although some modifications could be made to increase its speed, transportablity, and stability. The project was largely successful, and the following report is illustrative of a full design cycle for an engineering application.

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1 Introduction

Cranes have been a staple of large scale construction projects since the Ancient Greeks first started using them over 2700 years ago [1]. Modern cranes are used to lift heavier loads than ever before, and can use modern control techniques to be both safer and more efficient. The purpose of this project is to build a small scale, portable model of a modern bridge crane that can be used to demonstrate control techniques in a classroom setting.

2 Problem Understanding

2.1 Existing Devices

The following technologies are already in production and serve a similar purpose to the portable bridge crane that we will be creating. There are valuable lessons to be learned from how other engineers have solved similar problems to the one that we will be tackling, as can be seen below.

2.1.1 Existing Device #1: Dynamics Track

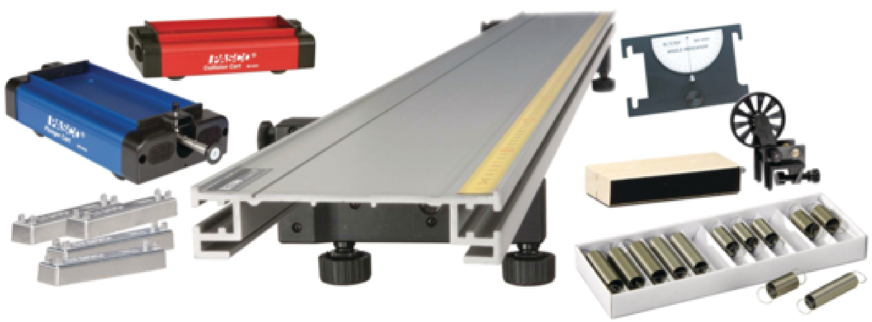


Figure 1: PASCO Dynamics Cart and Track (Source: PASCO Scientific)

Link: https://www.pasco.com/products/lab-apparatus/mechanics/dynamics-systems/me-5716
Description: This kit from PASCO includes two carts and a track, as well as various weights and other small add-ons. The carts have room for sensors to be added to them that can be used to show graphs of acceleration and velocity for instructional purposes. These can be used in a physics classroom to demonstrate collision mechanics for example. The track in this kit is 2.2 meters long, and one of the carts has a plunger spring on it to demonstrate collision mechanics. Although these carts are not powered, and the only crane element is a static pulley that can be attached to one end of the track, the purpose of demonstrating physics principles with moving carts is achieved by this device.

2.1.2 Existing Device #2: Miniature Gantry Crane

Figure 2: AICRANE Small Gantry Crane

Link: https://weihuagantrycranes.com/small-gantry-crane/
Description: The gantry crane is very similar to the bridge crane, providing another type of overhead lift, but a key difference is that its structure focuses mainly on the freestanding legs that operate on wheels. Usually, a bridge crane would be connected to an elevated support with rails, but due to our condensed version for the project, these two types of cranes boasts very similar designs. Our design also contains a single girder runway for a trolley holding the payload of which will provide the main mechanism in the design.

2.1.3 Existing Device #3: Vollmer 47905 Container Crane Model Kit

Figure 3: Volmer Plastic Model Crane

Link: https://www.modellbahnshop-lippe.com/Landscape+%26+Decoration/Trade+%26+Industry/Vollmer-47905/gb/modell_36627.html
Description: This is a plastic model kit of an overhang crane with a model cargo container. Despite it's small size, it still has the capability of moving across its rails and pick up the model container cargo. This model can represent the system, but it is not motorized, so it does not have any speed control and cannot move on it's own. However, it can extend it's cable length and move with physical assistance. An interesting feature to note is that in addition to the overhanging trolley being able to move, the model kit's frame has painted wheels, suggesting that the entire system can moves along a railroad track. Of course it's a plastic model, so it may not actually move, but it's a concept that can be explored.

2.2 Patents

2.2.1 Cable support for overhead crane trolleys US3833774A

This patent devises a solution for having cables being supported on the trolley without the tangling or drooping. The patent has the trolley suspended on a railway and the cable with the hook overhangs from the middle of the railway. The extra cable length is organized on the side of the railway so as the trolley moves to and fro, it will not be tangled and there are no overhanging stray cables. This patent is illustrated in Fig. 4.

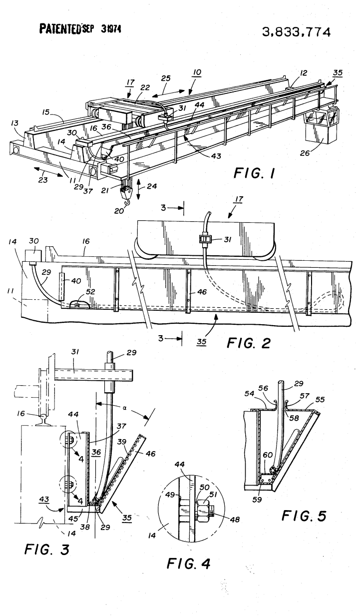
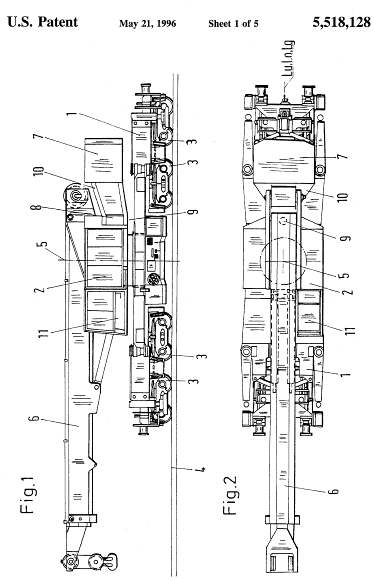


Figure 4: Illustration of Patent US3833774A

2.2.2 Crane, particularly railway crane US5518128A

Patent US5518128A uses an overhanging crane system that has a swivel from the top. The crane as a whole is able to move across rails using its trolley and utilizes a jib / counterweight system



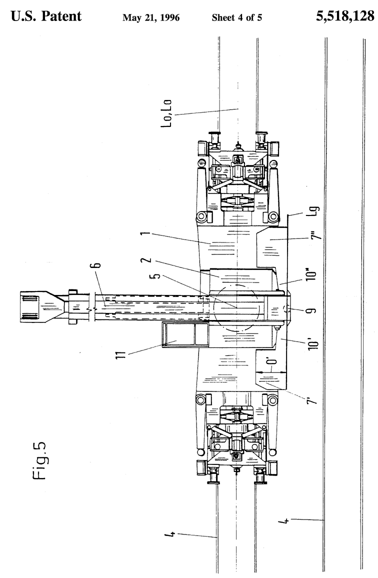


Figure 5: Illustration of the top and side view of US5518128A .

Figure 6: Illustration of US5518128A top view when crane is rotated.

when rotating the crane top. The cables are assumed to be hidden or stored on the trolley system itself. This patent is illustrated in Fig. 7 and Fig. 9.

2.3 Codes & Standards

2.3.1 ASME-Hooks: Safety Standard for Cableways,Cranes, Derricks, Hoists, Hooks, Jacks, and Slings (ASME B30.10-2019)

This standard has to do with the operation and maintenance of hooks for cranes, jacks, and other systems. We can apply the general safety and design guidelines at a smaller scale when designing the hook for our portable bridge crane. Furthermore, it can provide insight on how the hook can be attached to the payload and guidance on what scenarios to look out for to minimize hook failure and increasing durability of hooking on the payload.

2.3.2 NEMA: Motion/Position Control Motors, Controls and Feedback Devices (NEMA ICS 16-2001)

This standard has to do with the specifications and codes for the use of control motors, feedback devices, and controls. It will be useful both to see common specifications for stepper motors as well as to ensure that we operate the motors we buy properly. This can also help provide information on motor physical tolerances, best practices on attaching loads to the motors, and ideal motor performance settings.

2.4 User Needs

In order to better understand the scope of the problem, we interviewed the customer, Dr. James Jackson Potter. What follows is a summary of the interview followed by a table of specific needs interpreted from the conversation.

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Zoom Meeting
Date: February 4^{th}, 2021
Setting: The customer asked us to create a small, portable model of a bridge crane to use for demonstration purposes in a classroom setting. He described various qualities he would like the model to have. The whole interview was conducted online using Zoom, and took ∼35 min.

Interview Notes:

What control systems do you want?

- The motor must be capable of driving the trolley at different speeds using a program. The physical apparatus is what I am interested in.

Should we include soft stops?

- Include something near end that tells the cart to slow down so it doesn't run into hard stops at end of track

Must the cart remained attached to track when it is moved?

- It is not required for cart to remain attached to track.

Should it be capable of being disassembled and reassembled?

- Either way, it would probably be easy to make it in pieces anyway.

Can you think of any implicit needs?

- It does not need to look nice; it can show internal components. It does not need to be fully child-safe. It must fit through doors easily.

Do you have preferences for the materials we use?

- Don't use steel for everything. The weight should be low enough to carry around. Around 10 pounds is fine, less is ideal. No material constraints; can use wood, strong plastics, aluminum. Nothing that would give slivers. Light, strong. Don't use conduit.

What is the maximum pushing force the trolley should achieve?

- The payload should be light, but heavy enough that air resistance does not affect it. A stepper motor would be good.

What should the cable length be?

- 50 cm. The payload should be something like a tennis ball.

What do you want the maximum trolley speed to be?

– 1 foot/sec maximum speed.

Should the cable length be adjustable?

– It can be as simple as a hook. It can be adjusted manually.

How stable does the frame need to be?

– The frame will sway when the trolley stops, which can affect the swing of the payload. There should be limited sway when the trolley stops.

Should the system be battery operated or can it be plugged into the wall?

– Either way should be fine. You would need a high-voltage battery for a stepper motor. Do not worry about power saving.

Do we need to control the frequency of the payload?

– Do not worry about it, just move the trolley fast enough to make it start swinging

2.4.2 Interpreted User Needs

The following table of needs was interpreted from the customer interview above. Some of the more specific requirements that were discussed in the interview were interpreted in a more general way for the sake of ranking needs in this table.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	Variable Speed control for trolley	5
2	Adjustable cable lengths	5
3	Lightweight	4
4	Ease of transportation	5
5	Power efficient/Battery operated	1
6	Visible to large audience from far away	4
7	Durable for multiple uses	3
8	Track has soft stops	3
9	System can be disassembled and reassembled	2
10	Overall Safety	2
11	Frame vibrations are limited	4
12	Cable is adjustable automatically	1
13	Aesthetics	1

As can be seen in the table above, the most important needs are the variable speed control, adjustable cable lengths, and ease of transportation. To not meet these needs would be to design the wrong product, which is why they are at such a high priority. Many needs are in the range from 3-4, meaning that they are important to consider but that there is more room for error. The needs in the 1-2 priority range are either nonessential features that the customer would like to have in the final product, or general concerns (such as aesthetics and efficiency) that are not as important when designing the product.

2.5 Design Metrics

The following table of target specifications was developed with the customer needs listed above in mind. Each entry represents a testable metric relating to one or more customer needs. The last two metrics come from the standards discussed above.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1,8	Total speed	cm/s	30 ±10	30
2	2,12	Number of Length settings	*integer*	≥2	≥5
3	3,4,9	Mass	*kg*	< 9	< 5
4	5,13	Distance where audience can see payload	*m*	> 15	> 30
5	11	Max frame vibration amplitude on stopping	*mm*	< 5	< 1
6	8	Has soft stop	*binary*	*No*	*Yes*
7	5,10	Motor input voltage deviation from rated value NEMA ICS 16-2001 (NEMA)	*percent*	±10%	±5%
8	10	Removal Criteria for distortion of hook's throat opening B30.10 - 2019 (ASME)	*mm*	6	3

3 Concept Generation

3.1 Mockup Prototype

We found that the load, while swinging, was prone to hitting the frame. Although we found that the crank mechanism worked rather well, it seemed like it would get loose after using it for a while. We need to hang the crank from the track, or we want a hole on the bottom of the track. We need to limit vibrations because as the weight swings, the frame sways. We found that we need guards on the edges so that the trolley doesn't fall off. It should be obvious, but we if we want motors on the trolley, having wheels rather than rollers would be simplest. For visibility's sake, we can make the cart bright, the track dark, use a bright yellow tennis ball as the payload, and use a dark background.

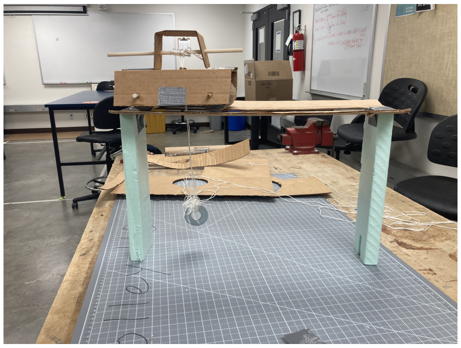


Figure 7: Trolley and frame

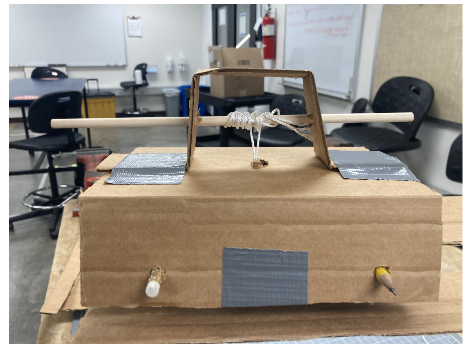


Figure 8: Close up view of trolley

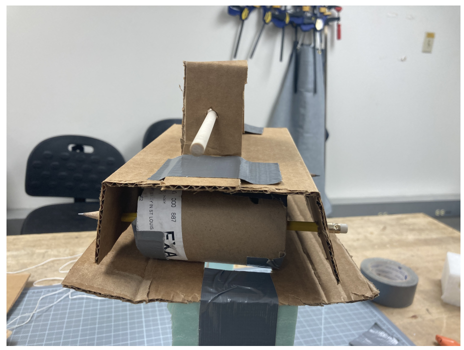


Figure 9: Side view of trolley and tracks

3.2 Functional Decomposition

Upon discussion on the mockup's insights and our own individual function tree, we developed a team Function Tree, as illustrated in Fig. 10

- Trolley cart moves across a track to demonstrate dynamics and controls to an audience
  - Trolley must have stable movement across the track
  - Cable length is adjustable
  - Soft stops/limit switch to restrict trolley momentum
  - Has a speed control
  - Transportable
  - Frame has to be stable / limited vibrations
  - Provide energy to controller and moving parts

Figure 10: Function Tree for Trolley System

3.3 Morphological Chart

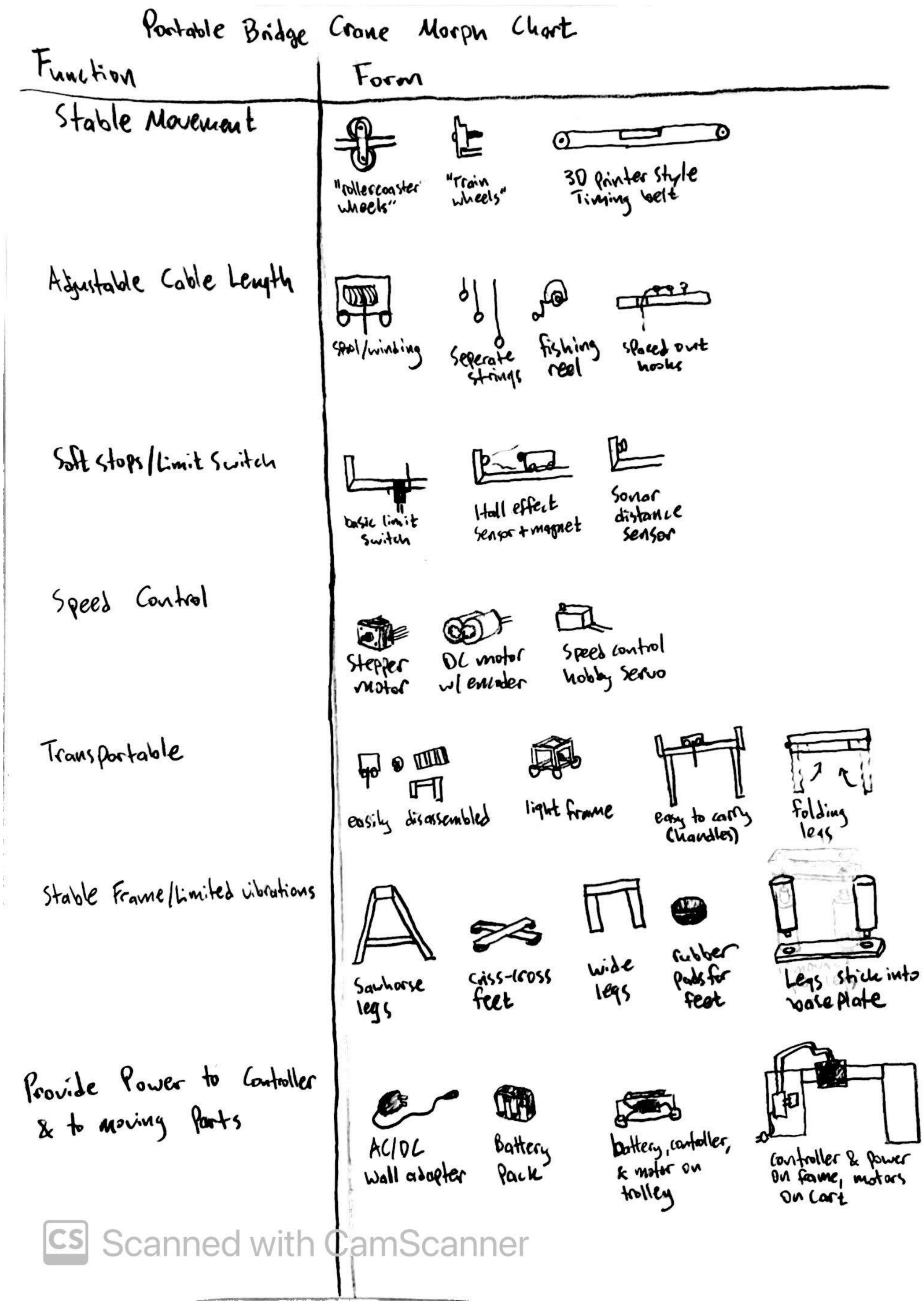


Figure 11: Morphological Chart for Trolley Designs

3.4 Alternative Design Concepts

3.4.1 Rod Frame Fishing Trolley (Justin Wan)

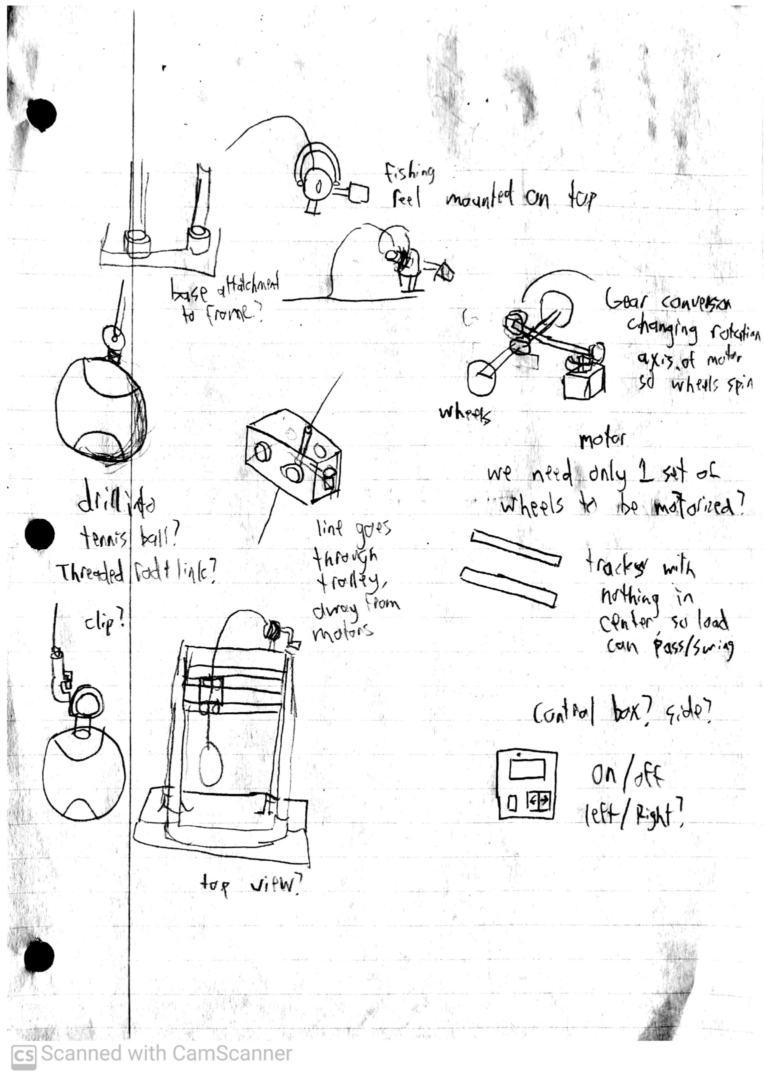


Figure 12: Preliminary sketches of thin rod, fishing rod trolley concept

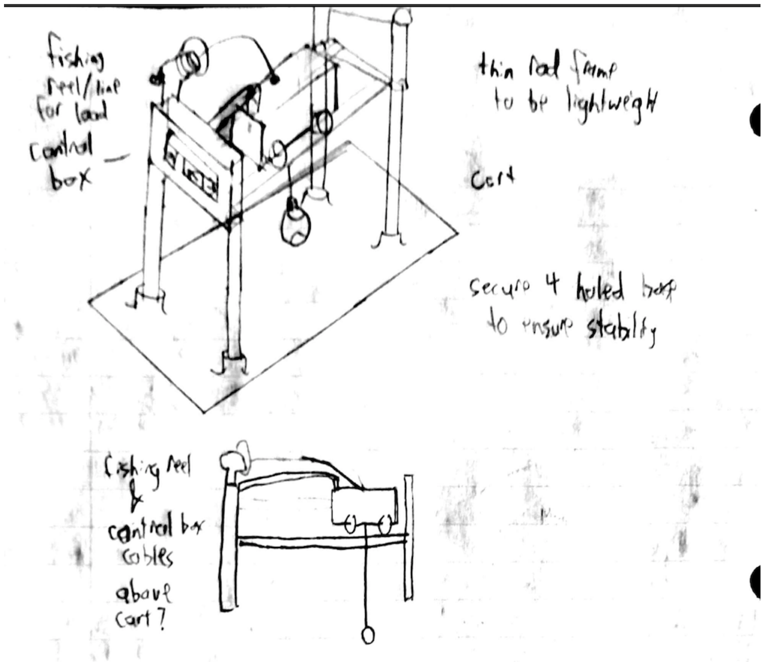


Figure 13: Final sketches of Rod Frame Fishing Trolley concept

Description: Design concept using a fishing rod to keep the load attached to cart and adjust the length. The trolley will have a motor that powers the set of wheels closest to the control panel and controls the left right, on, off movement. The base of the entire system will have holes to prop up the rods and provide stability. The rod design also allows the load to oscillate without risk of hitting the frame.

3.4.2 The Jolley Trolley (Mitry Anderson)

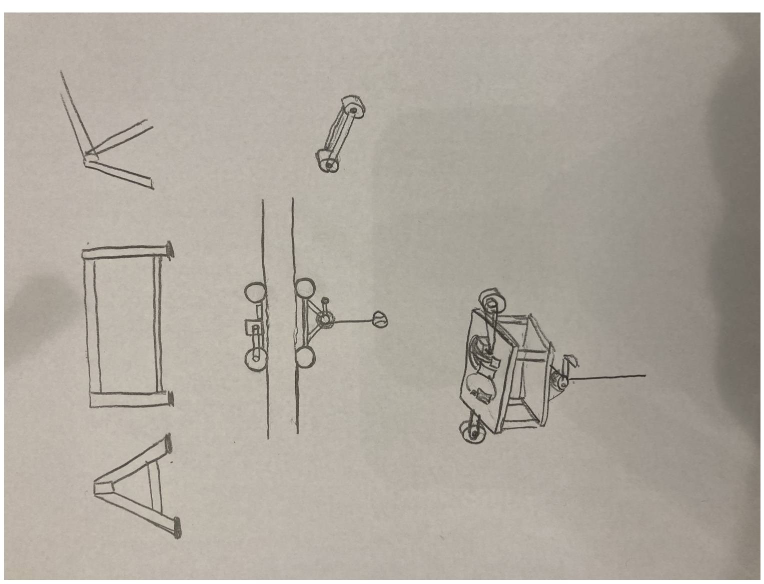


Figure 14: Preliminary sketches of the frame, trolley, and so on

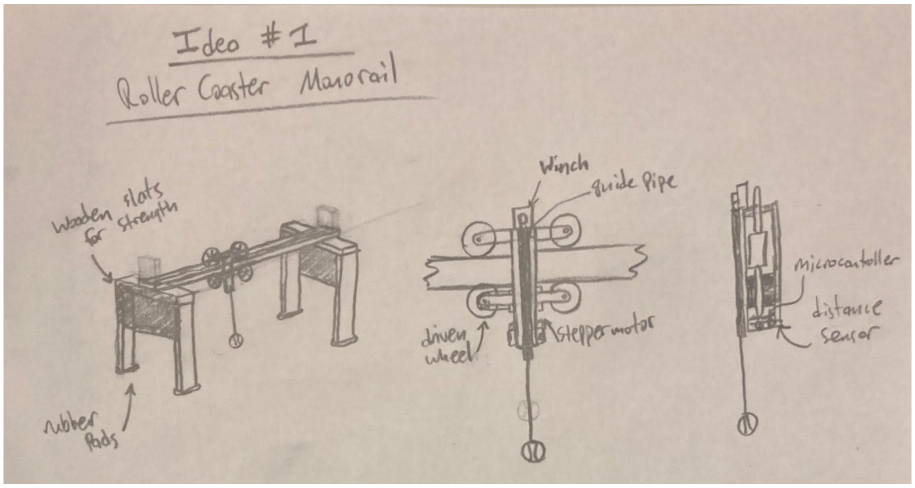


Figure 15: Final sketches with three views

This concept is inspired by roller coaster wheels, which hold on to the track from multiple directions for stability. The cart can hang from the track like a monorail, and have the motor and driver boards contained on board. The automatic winch is optional, that could be replaced with a simple crank.

3.4.3 Split Track (Bethany Starr)

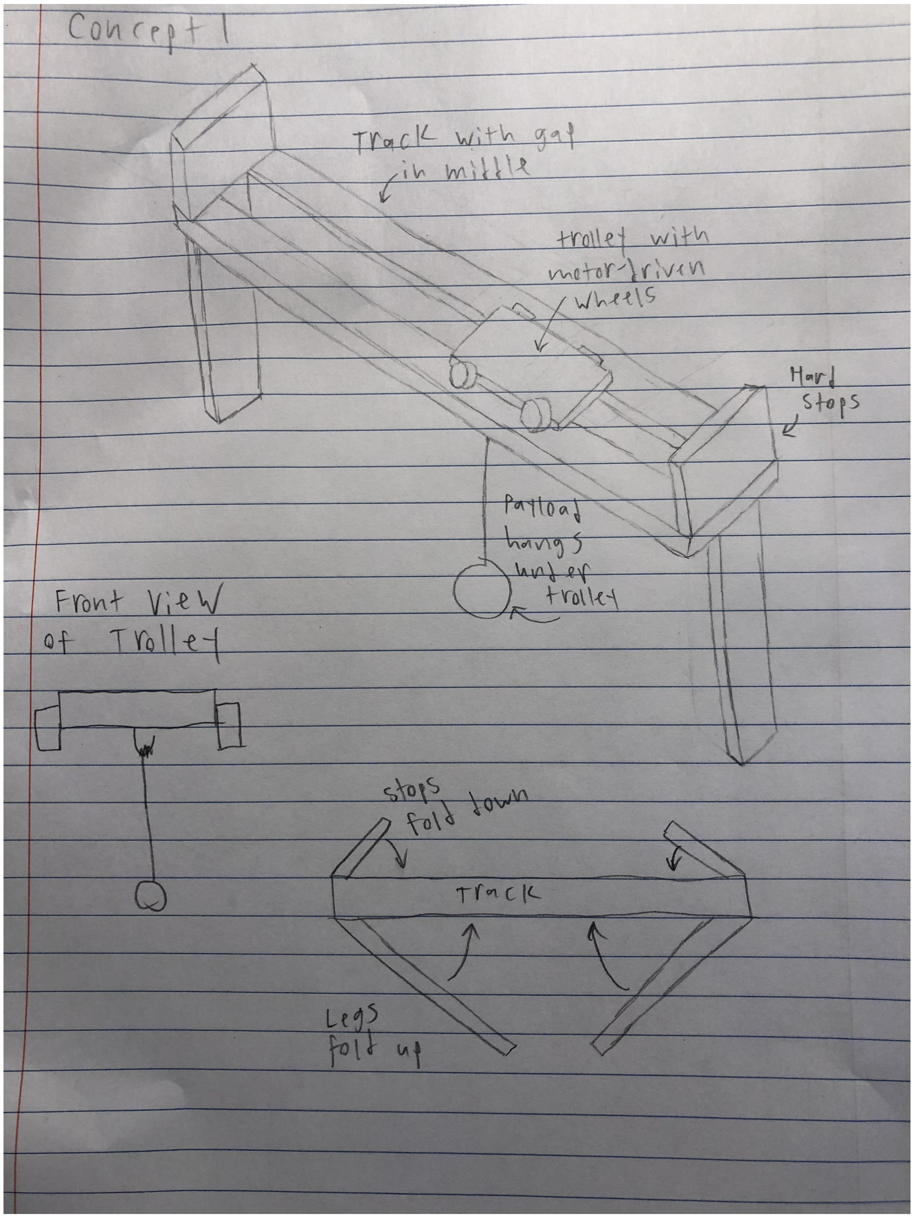


Figure 16: Sketch of the entire system plus a cross-section of the trolley and a sketch on how the system may fold

This concept was meant to be the simplest possible design. The motor-driven trolley runs down a track split into two parts with the payload falling in the gap in the middle. The payload is attached to the trolley via a simple hook, with the cable length adjustable by wrapping and unwrapping the cable around the hook. However, an automatic winch could easily be substituted in. The hard stops and legs can fold against the track for easy transportation.

3.4.4 Split I-Beam Track (Bronson Wu)

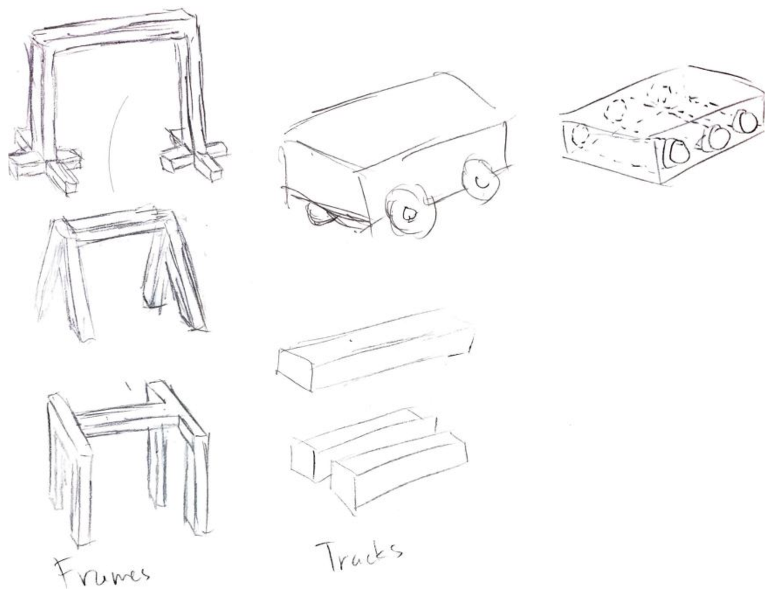


Figure 17: Preliminary sketches of frames, trolley and track

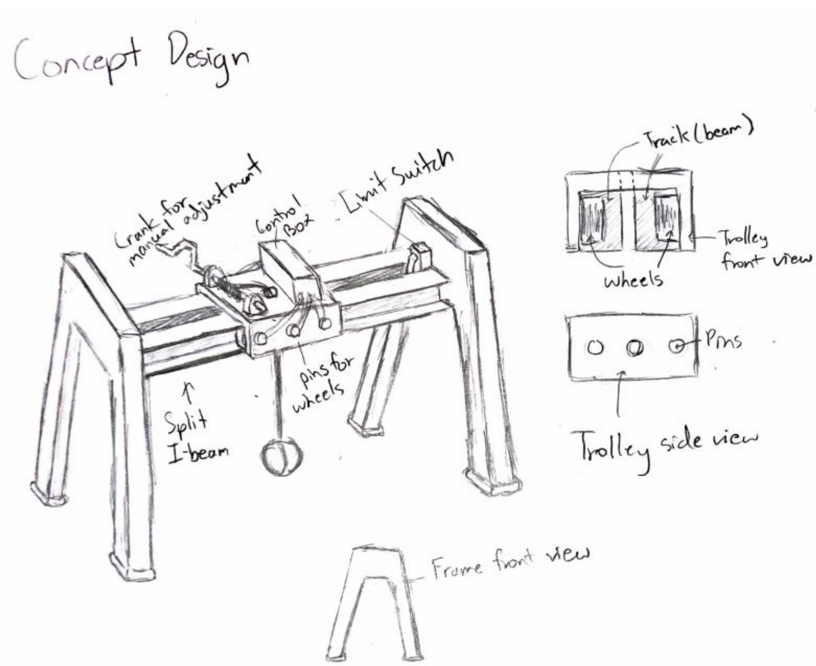


Figure 18: Final Design Concept

This design concept showcases a relatively simple frame design with a split I-beam track. The wheels of the trolley are secured by pins and ran by the motor connected to the control box. In addition, the payload rope is securely fastened to a manual crank. It is then threaded through a small opening in the middle of the box and through the track opening. A limit switch is placed at the ends of the track.

4 Concept Selection

4.1 Selection Criteria

Upon discussion, our group found that Portability, Safety, Visibility, Usability, and Stability were the main criteria. We decided that the ease of transport held the most importance. The system should not be very hard to use, so it was second most important. Stability and visibility to audiences were considered nice to have but not essential. Safety was ranked the lowest because the system does not have any parts that will maim, blind, or kill a person and will not be operated near children. The Analytical Hierarchy Matrix is illustrated in Fig. 19.

	Transportable	Safety	Visibility	Usability	Stability		Row Total	Weight Value	Weight (%)
Transportable	**1.00**	5.00	3.00	2.00	3.03		14.03	0.32	31.77
Safety	0.20	**1.00**	0.20	0.20	0.33		1.93	0.04	4.38
Visibility	0.33	5.00	**1.00**	0.20	0.33		6.87	0.16	15.55
Usability	0.50	5.00	5.00	**1.00**	2.00		13.50	0.31	30.57
Stability	0.33	3.00	3.00	0.50	**1.00**		7.83	0.18	17.73
						Column Total:	**44.16**	**1.00**	**100.00**

Figure 19: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

After finding a weighting that would work for the five main criteria, we proceeded to compare the four solutions we had generated previously against these criteria. The solutions were given scores from 1 to 5 in each category, with 1 being the lowest and 5 being the highest. The results of this analysis can be seen in Figure 20, which shows the score that each proposed device had for each category, as well as the weighted scores for each category and the final weighted scores.

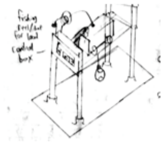
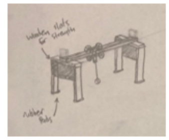
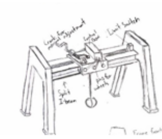
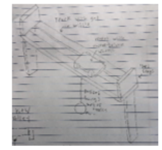
Alternative Deisgn Concepts		Concept #1		Concept #2		Concept #3		Concept #4	
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Portability	31.77	2	0.64	3	0.95	3	0.95	5	1.59
Safety	4.38	2	0.09	3	0.13	4	0.18	3	0.13
Visibility	15.55	4	0.62	4	0.62	4	0.62	4	0.62
Usability	30.57	4	1.22	4	1.22	4	1.22	4	1.22
Stability	17.73	5	0.89	3	0.53	4	0.71	2	0.35
	Total score	**3.454**		**3.461**		**3.682**		**3.919**	
	Rank	**4**		**3**		**2**		**1**	

Figure 20: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

The weighted scoring matrix models were a key component to the analysis of all four of our concept designs. The result of the weighted scoring matrix was that Bethany's design was weighted the highest due largely to the high rank in portability. This design was considered so portable because it had a mechanism for easily folding the legs to make it more compact during transit. Additionally, this design performed well in the other categories, being generally usable and easy to see.

However, the group believed there were merits in the other designs as well. As a result, we will take the best attributes of each design into consideration while developing our future prototypes as well as our final design. Notably, our final design will incorporate a folding mechanism for portability, rubber pads for stability, a belt driven system (to avoid having that heavy stepper motor on the trolley itself), and a bright neon green tennis ball for ease of visibility.

4.4 Engineering Models/Relationships

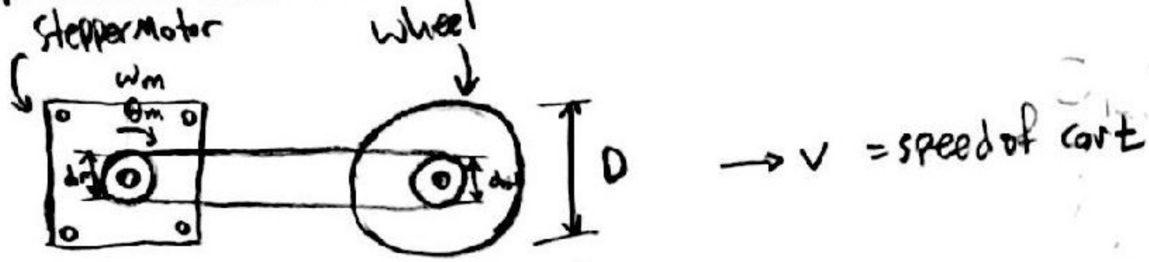
4.4.1 Model 1: Stepper motor speed to trolley speed conversion

The first Engineering model we find potentially useful was an equation to convert between the speed of the trolley and the number of steps per second required of the stepper motor. This is illustrated in Eqn.1, where d_w is the diameter of the pulley attached to the wheel, d_m is the diameter of the pulley attached to the motor, D is the diameter of the wheel, and v is the desired trolley velocity. This model assumes that the stepper motor has as step angle of 1.8 degrees per step. This will allow us to understand how the sizing of the wheels and pulleys will affect the final speed of the cart, which we know needs to be around 1 foot per second.

$$n = \frac{v d_w}{50\pi D d_m} \left[\frac{steps}{s}\right] \tag{1}$$

The full derivation for this equation is shown below. The equations for how the gear ratios work for the pulleys can be found on page 628 of Shingley's Mechanical Engineering Design [2].

Stepper Motor Anglar speed conversion model



θ_m = angular displacement of motor
d_m = diameter of timing belt pulley on motor
D = wheel diameter
ω_m = angular speed of motor
n = steps/second
ϕ_n = degrees/step $= 1.8^\circ$
d_w = diameter of wheel timing belt pulley
ω_w = angular speed of wheel

$$\omega_m = \phi_n \cdot n \cdot \frac{\pi}{180}$$

$$\omega_m d_m = \omega_w d_w \rightarrow \omega_w = \frac{\omega_m d_m}{d_w}$$

$$v = \frac{D}{2}\omega_w = \frac{D}{2}\frac{\omega_m d_m}{d_w} = \frac{D}{2}\frac{\phi_n \cdot n \cdot \frac{\pi}{180} d_m}{d_w}$$

$$v = 50\pi \cdot D \cdot n \cdot \frac{d_m}{d_w}$$

so if we want to move @ speed v, need

$$\boxed{n = \frac{v\, d_w}{50\pi D d_m}\left[\frac{\text{steps}}{s}\right]}$$

Figure 21: The derivation for Eqn.1

4.4.2 Model 2: Critical Buckling Load

The second Engineering model that we find useful is the buckling equation below. This is labeled as Eqn. 2.

$$P_{CR} = \frac{\pi^2 EI}{L_e^2} \tag{2}$$

In Eqn. 2, E is the Young's Modulus, L_e^2 is the column length, and I is the cross sectional area moment of inertia. This equation is found from the MEMS 3110 Machine Elements Deflection lecture [3]. This equation can be useful to help calculate the maximum weight or load that each leg of the system can withstand. Since there are 4 legs, it is assumed that the legs will be withstanding a distributed load $\frac{1}{4}$ of the maximum weight that the rails, trolley, and control system can be. This can also be used to identify what materials we want the legs to be made of, what shape the legs can be, and the minimum length the legs can be.

4.4.3 Model 3: Stepper Motor Resonance

The third Engineering model that we find useful is the resonance frequency model for a stepper motor. The significance in this model lies in the fact that the trolley may potentially stall when the excitation frequency, due to induced vibrations, matches with the stepper motor's resonance frequency. The resonance frequency is calculated in Eqn. 6, where p is the number of magnetic poles in the stepper motor, τ_h is the holding torque, and $_r$ is the rotor inertia [4].

$$f = \frac{100}{2\pi}\sqrt{\frac{2p\tau_h}{J_r}} \tag{3}$$

5 Concept Embodiment

5.1 Initial Embodiment

5.1.1 CAD Model Images

Figure 22: Top View of Prototype

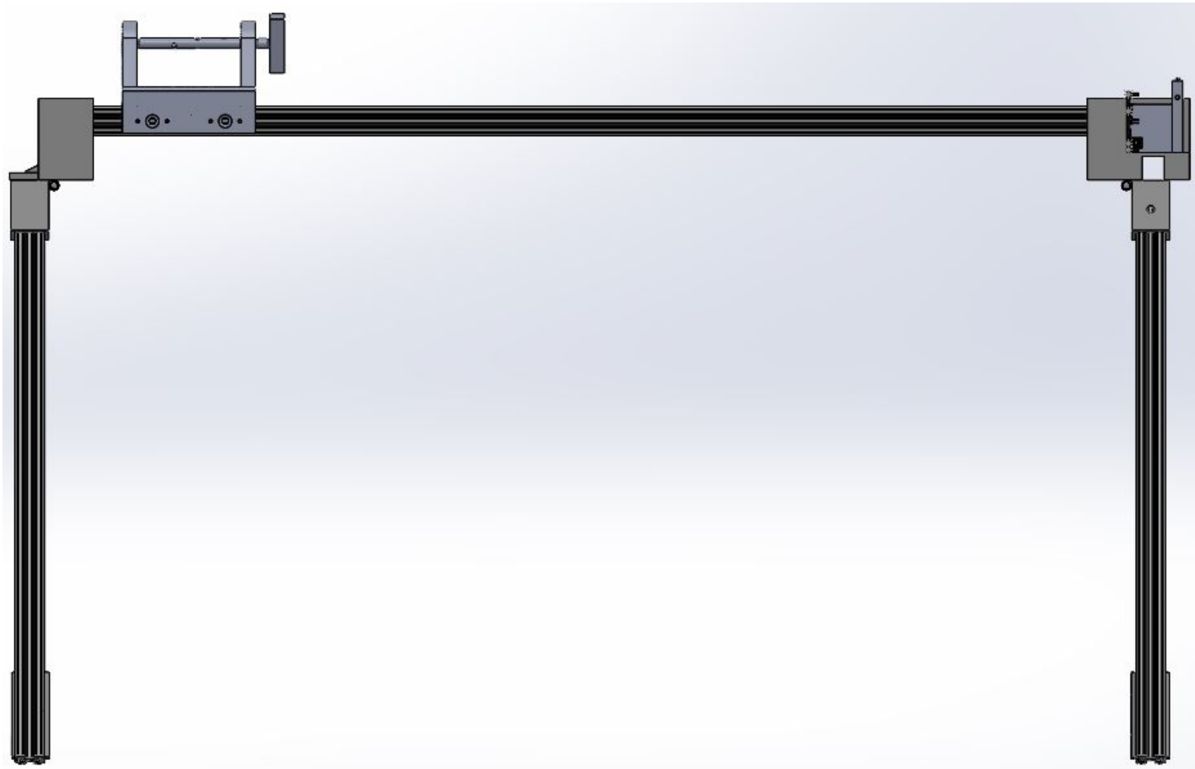


Figure 23: Right View of Prototype

Figure 24: Right View of Prototype with Folded Legs

Figure 25: Front Side View of Prototype

ITEM NO.	PART NUMBER	QTY.
1	Aluminum Frames	8
2	Hinge 1	2
3	Hinge 2	2
4	Top Bracket	2
5	End Bracket	4
6	Timing Belt Plate	1
7	Trolley	1
8	Trolley Bearings	8
9	Holder 1	1
10	Holder 2	1
11	Spool	1
12	Spool Cap	1
13	Arduino Leonardo	1
14	Breadboard	1
15	Motor	1
16	Pulley	2

Figure 26: Isometric View with Callout to BOM

ITEM NO.	PART NUMBER	QTY.
1	Aluminum Frames	8
2	Hinge 1	2
3	Hinge 2	2
4	Top Bracket	2
5	End Bracket	4
6	Timing Belt Plate	1
7	Trolley	1
8	Trolley Bearings	8
9	Holder 1	1
10	Holder 2	1
11	Spool	1
12	Spool Cap	1
13	Arduino Leonardo	1
14	Breadboard	1
15	Motor	1
16	Pulley	2

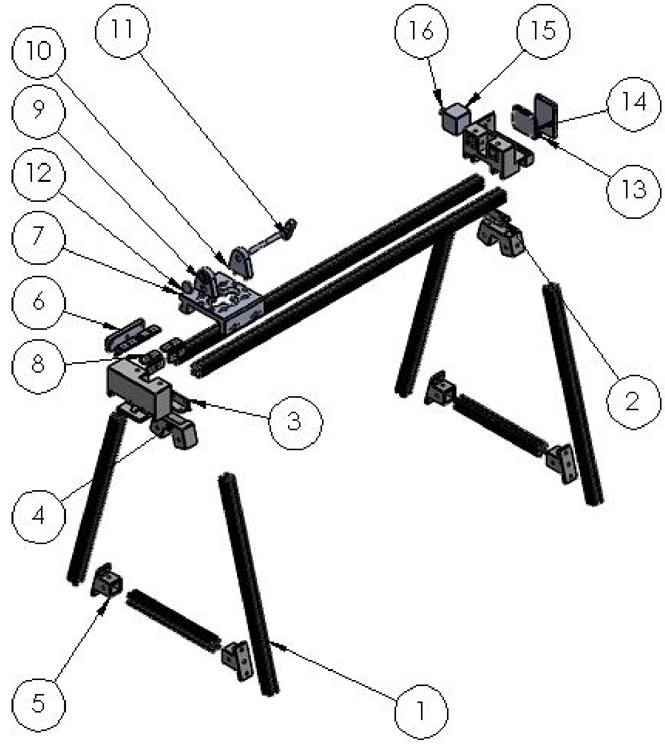


Figure 27: Exploded View with Callout to BOM

5.1.2 Basic Dimensions

Height from bottom of leg to top of spool: 60.02cm
Width between leg bottoms: 31.47 cm
Length between both pairs of legs: 100.6 cm

5.1.3 Prototype Performance Goals

For the design of the portable bridge crane, the performance goals are as listed:

1. The trolley can move at a speed $\geq$ 1 ft/sec.
2. The trolley can move in both directions and must stop before reaching the end of the rails.
3. The entire prototype must weight less than 10 lb.

5.2 Proofs-of-Concept

When working on the Proof-of-Concept prototype, there were multiple areas we found that needed to be fixed or updated on the Initial prototype. Specifically, on the rail, trolley, and frame.

When working with the aluminum rods as our rail, we realized its simplicity was a virtue due to how easy it was to attach to the wooden frame. However, we had a hard time figuring out how we can make for smoother sliding. It was thought that a linear motion bearing would work, but it was hard to find an exact fit to the aluminum rod in hand. Because of this, we decided it would be better to transition towards vendor parts from McMaster-Carr. In addition to having sliding bearings that are designed to fit on the aluminum McMaster-Carr rails, we can use those McMaster-Carr rails to serve as legs as well.

The Proof-of-Concept's trolley also helped illuminate potential issues with how the timing belt will fit on the trolley and the stepper motor/ pulley. On the Proof-of-Concept, the part where the timing belt hole fits on the trolley was misaligned, making the timing belt to misshapen. This can have adverse affects on the sliding of the trolley the and potentially interfere with the payload. This is illustrated in Fig. 28 .

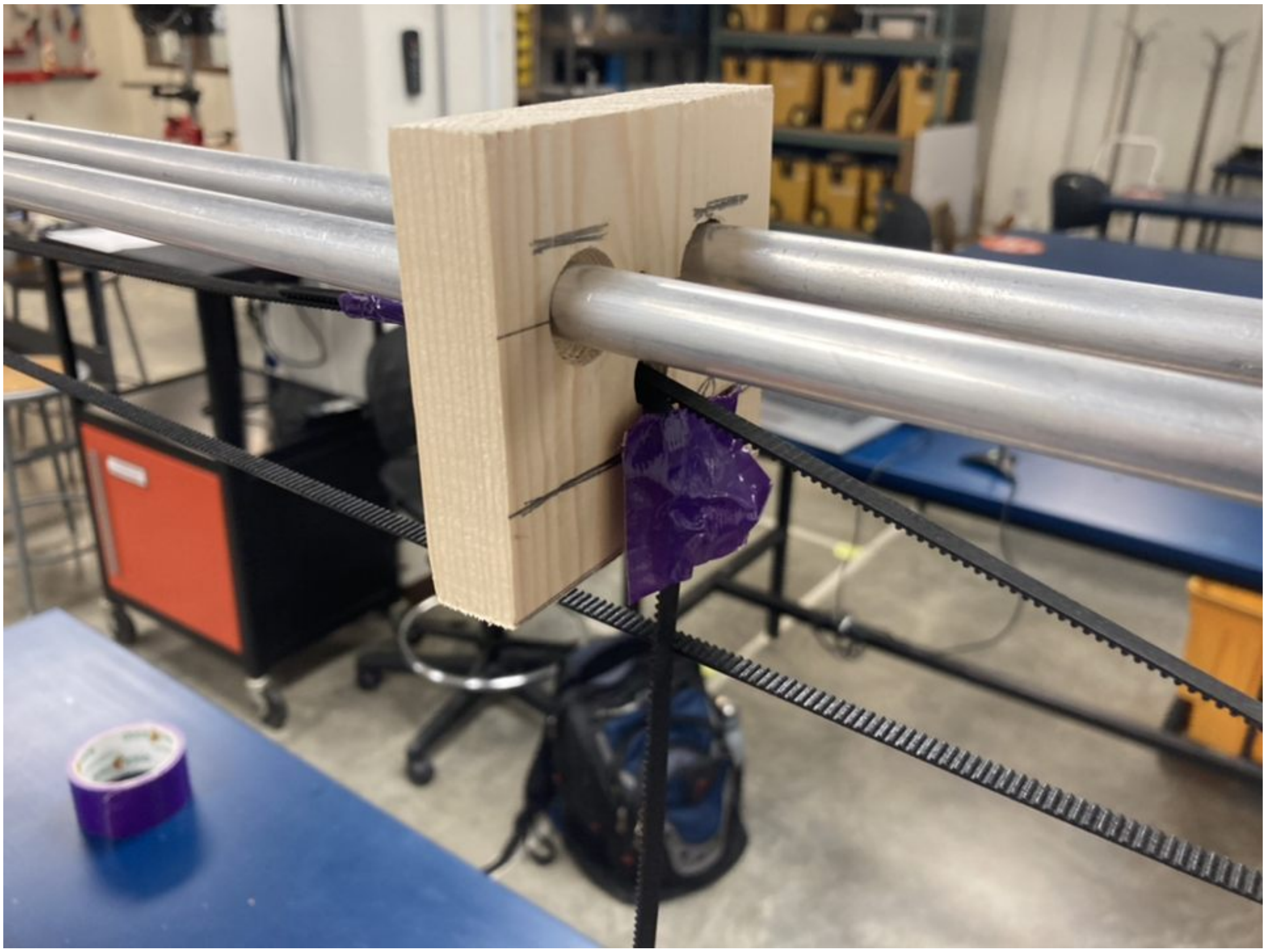


Figure 28: Proof of Concept Trolly

As mentioned above, the frame had undergone design changes the Proof-of-Concept. In the Proof-of-Concept, we made the frame out of wood and it sits as 1 single unit, as seen in Fig.29 . This would not be very stable or portable, so the design will change to be closer to the concept selection. Furthermore, instead of wood, we decided that the McMaster-Carr rails will be used as legs for simplicity sake.

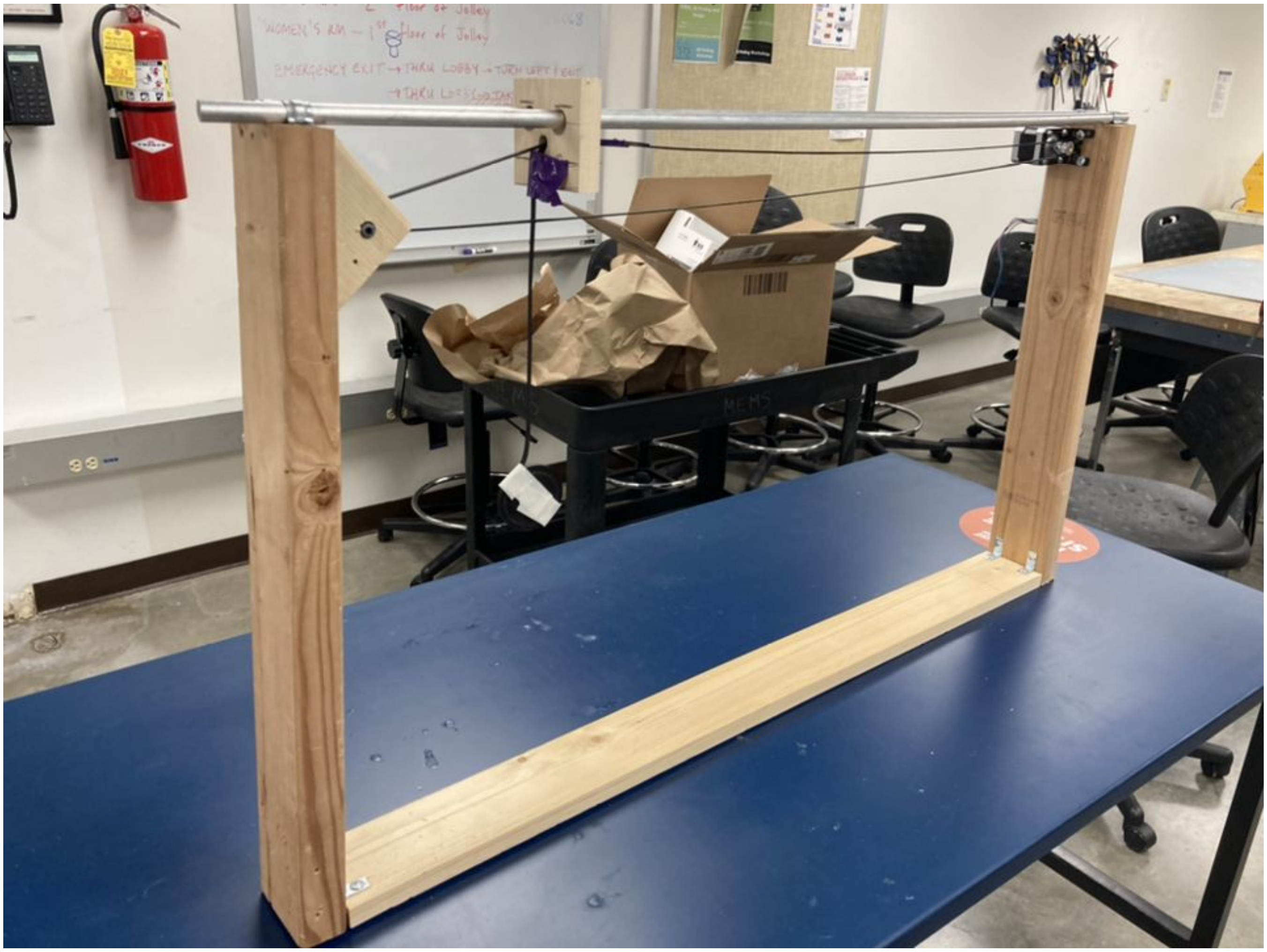


Figure 29: Proof of Concept Frame

5.2.1 Initial Prototype Changes

When we chose Concept 4 as the selected concept in the Concept Selection, we choose this concept primarily for the ease of trans-portability. However, we did like other aspects from the other concepts and new design choices. At first glance, the Initial Prototype looks very close to Concept 3, and not so much concept 4. However, the Initial prototype follows the spirit of what made Concept 4 such a compelling choice: the folding mechanism. As illustrated in Fig. 24 the initial prototype can fold for ease of transport. The Initial Prototype does follow along with Concept 4's design for having the payload hang under the trolley between the gap in the track.

One of the design aspects that differ from Concept 4 was the inclusion of an A frame. Though not explicitly stated, the A frame design was borrowed from Mitry's Jolley Trolley sketch. This frame provides good stability while keeping the frame light and portable. In addition, the design choice for a manually adjusted payload crank was borrowed from Concept 3.

A final point of divergence with the Initial prototype was the incorporation of the timing belt mechanism. This was not found in any of the concepts. As mentioned in section 4.3, the rationale to this addition was to reduce the weight of the trolley by having the stepper motor be attached to the frame instead. The stepper motor and timing belt also provides fine control for how many steps are needed for the trolley to traverse the entire length of the system.

6 Design Refinement

6.1 Model-Based Design Decisions

The models discussed earlier in this report were used to make design decisions during the design of The Jolley Trolley.

6.1.1 Model 1: Stepper motor speed to trolley speed conversion

Earlier, a formula was derived to find the number of steps per second required to achieve a desired travel speed of the trolley. This equation was originally meant to be used for a situation where the trolley was a cart moving along the track, rather than the design we ended up using where the trolley was pulled by a belt. A modified version of the equation is given below, which was used to calculate the stepping time for our case, where ϕ is the number of steps in a revolution, v is the desired speed, D is the pulley diameter, and t is the number of seconds in between steps.

$$t = \frac{pi * D}{\phi v} \tag{4}$$

With a ϕ of 200, D of 0.6in (0.05ft), and v of 1ft/s, a stepping time of 785 microseconds was calculated, as shown below.

$$t = \frac{pi * 0.05}{200 * 1} = 0.000785s \tag{5}$$

This is the time that we need to use in the actual program to drive at 1 foot per second. In terms of frequency, this is 1274Hz.

Of course, this model assumes that the belt will not slip and that no steps will be skipped during the operation. It also assumes that the motor will be operated with a constant speed, so this equation will not hold true while the motor is accelerating. Also, the speed will be controlled in an open loop system, so there will be no way for the micro controller to verify that the actual speed is truly the same as the calculated speed.

6.1.2 Model 2: Critical Buckling Load

The equations we had found earlier for buckling didn't make much sense to use with our A-Frame design, so instead we did some brief calculations to find the maximum load required to break the legs. The process is outlined in the notes below, and involved finding the static forces in each joint, then doing some rough stress calculations.

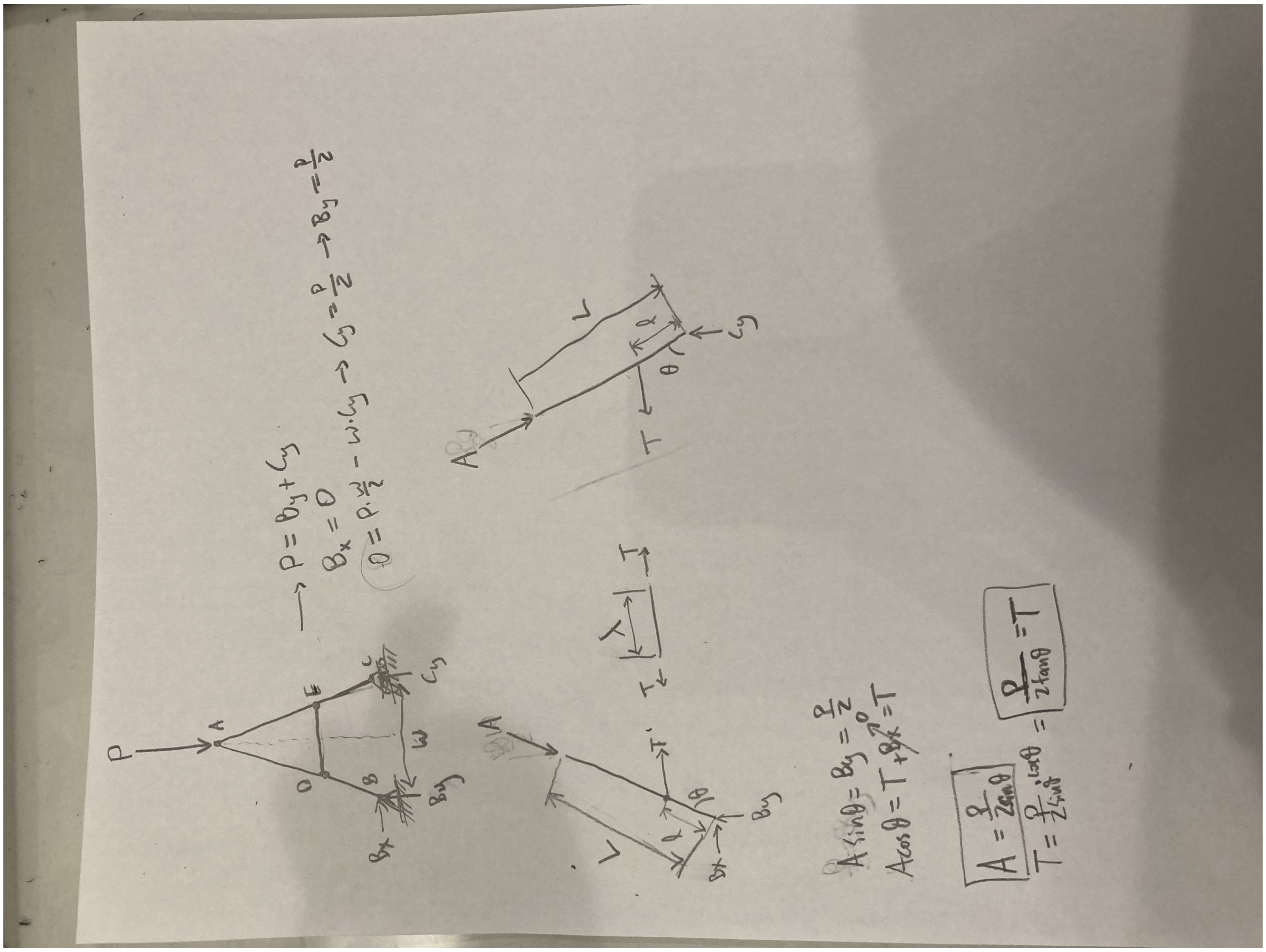


Figure 30: Finding the forces

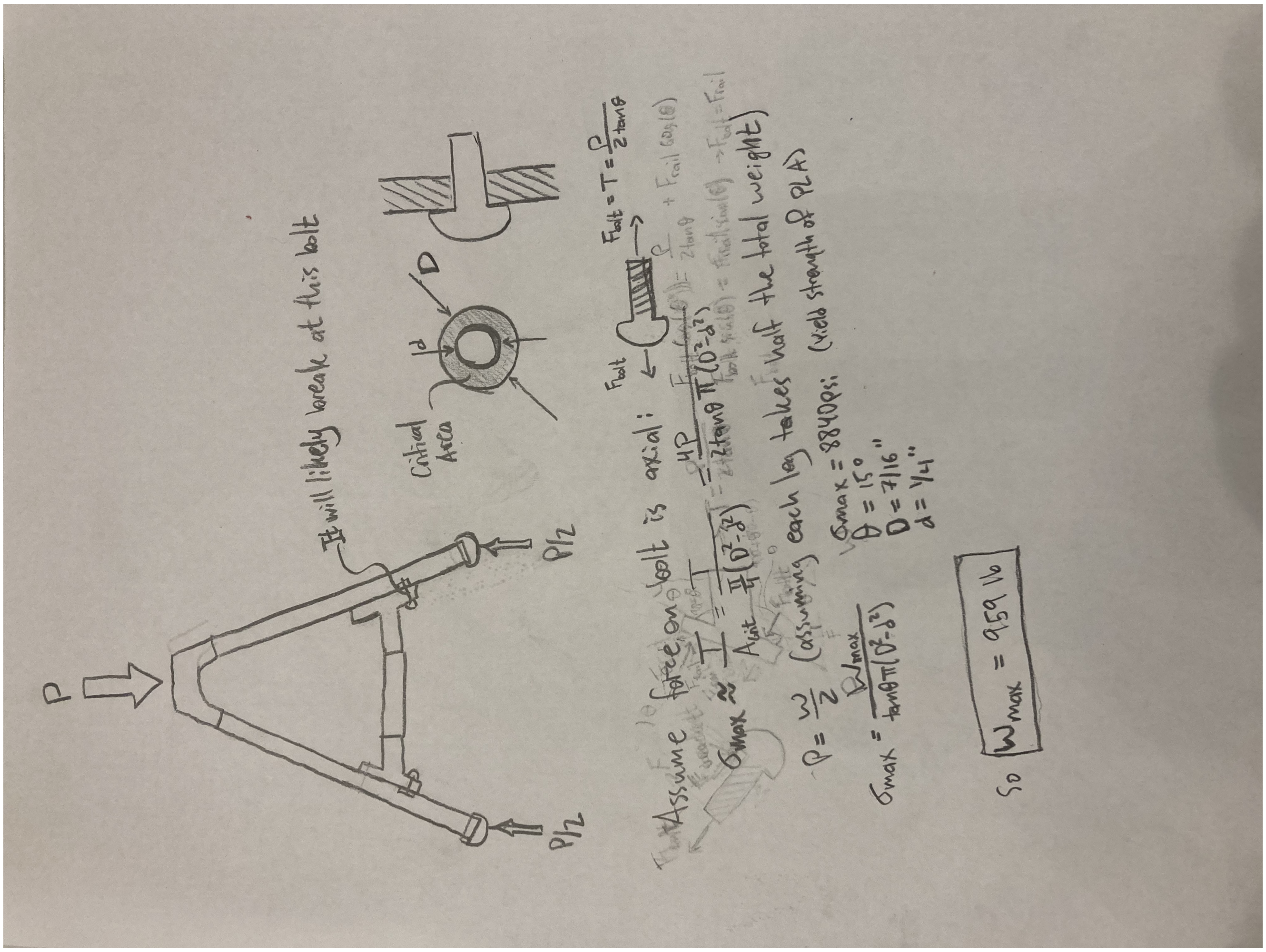


Figure 31: Finding an approximate maximum stress.

More complicated and precise failure-prediction methods are available, but for our simple case it is not necessary as the device will not be operating close to its maximum conditions. We assumed the yield strength of the PLA was 8840psi[5], the outer diameter of the bolt head was 7/16", the screw diameter was 1/4", and the angle of incline was 15 degrees. With this, a maximum load of 959lbs was calculated, which is likely higher than reality. However, even with a safety factor of 3 a person could probably still stand on the device, which would not be a common case, so we have concluded that PLA will be strong enough for use in our device.

6.1.3 Model 3: Stepper Motor Resonance

The earlier equation for stepper motor resonance was used to find the resonant frequency for the stepper motor. The motor is bipolar, with a rotor inertia of $140\frac{kg}{m^2}$, and a holding torque of $0.18Nm$ [6], as shown below.

$$f = \frac{100}{2\pi}\sqrt{\frac{2 * 2 * 0.18}{140}} = 1.14Hz \tag{6}$$

A resonant frequency of 1.14Hz was calculated, which is well below the frequencies we will be driving the motor at. This allows us to verify that the motor is safe to use at our frequency of around 1200Hz.

This model assumes that our individual motor perfectly matches the data sheet for its torque and inertial properties. It also assumes that there will only be one resonant frequency, but there could theoretically be resonance at higher frequencies that were not calculated with this equation.

6.2 Design for Safety

6.2.1 Risk #1: Support Collapse

Description: Vibrations from the motor during operation may weaken or shake the connections in the A-frame. This can potentially lead to a collapse in the system, whether it be through the A-frame folding in prematurely or the A-frame falling apart .

Severity: Critical

Probability: Unlikely

Mitigating Steps: Steps to mitigate this instability would be to incorporate tighter connections between the parts, especially the joints and hinges. These can be done through more precise analysis of the types of fitting between the parts. In addition, a clip system can be used to ensure the structure stays upright or stays folded.

6.2.2 Risk #2: Material Sharpness

Description: The materials used in the design can have sharp edges left un-sanded or uncovered of which can potentially harm the user when coming into contact.

Severity: Marginal

Probability: Seldom

Mitigating Steps: This can be mitigated by sanding or covering any possible sharp edges in the design and incorporating fillets.

6.2.3 Risk #3: Timing belt Snapping

Description: With use of the timing belt, it can potentially snap due to excessive tension on the belt and overall durability wear and tear at the belt teeth. In addition, it could be misaligned with the connection to the trolley.

Severity: Catastrophic

Probability: Unlikely

Mitigating Steps: The best way to mitigate the timing belt from snapping would be to orient it in the correct position along the track, and to make sure the timing belt is not too tight.

6.2.4 Risk #4: Frame Pinch points

Description: There is a chance that the hinges can pinch the users fingers when they are setting up the trolley

Severity: Marginal

Probability: Occasional

Mitigating Steps: The system has been set up so that during the unfolding of the frame, there is ample space to grip each end of the A-frame and prop it upright without being close to the hinges.

6.2.5 Risk #5: Payload Hitting User

Description: When moving at an appropriately fast speed across the track, the payload can potentially hit the user if they are positioned directly in front of the opening between the aluminum leg frames.

Severity: Negligible

Probability: Unlikely - Occasional (depends on user's positioning)

Mitigating Steps: Have the user position themselves away from the range of the payload rope's radius when the trolley starts moving.

6.3 Risk Prioritization

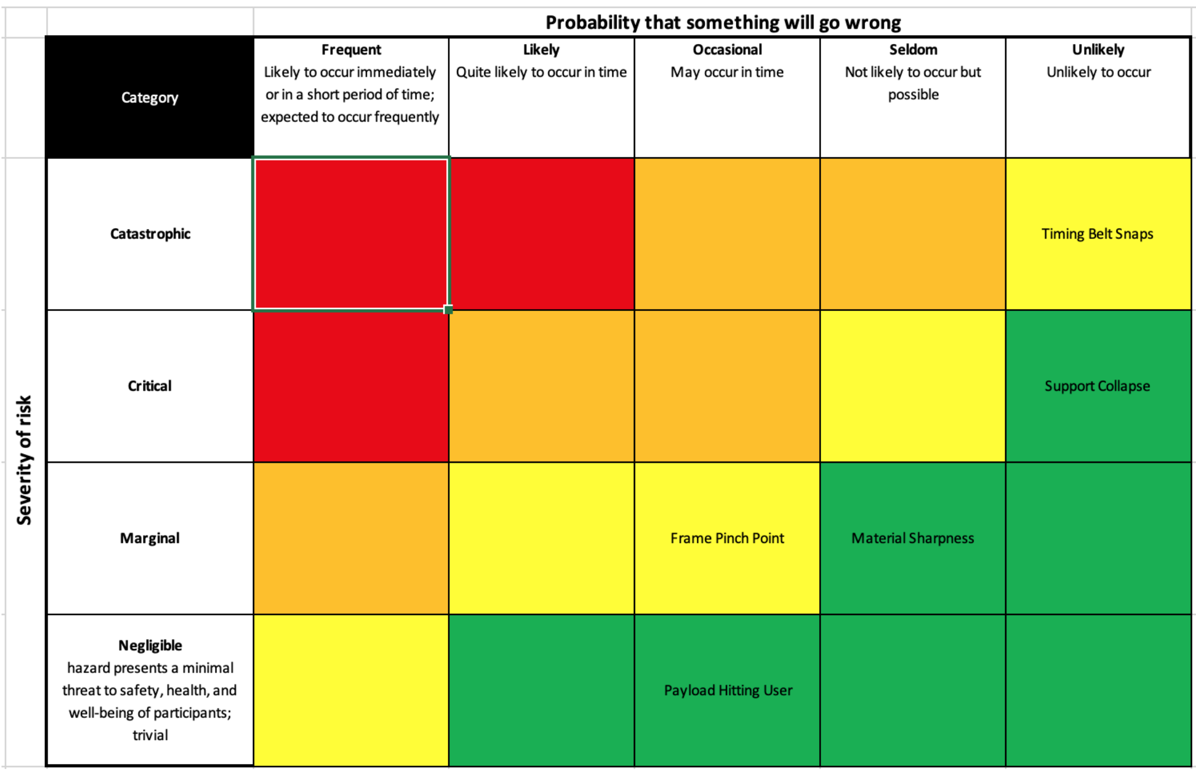


Figure 32: Updated Heat Map

Considering Fig. 32, the risk of timing belt snap will have the highest priority because the entire system will be unusable if there is not fix or timing belt replacement, and if the user happens to be present during the belt snap, the whiplash will inflict the most bodily harm. The second risk to consider would at the frame pinch point because it is a risk that can occur frequently, albeit the bodily harm inflicted is fairly minor. A collapse in support followed by material sharpness and payload hitting the user are the next risks, but these are not as serious because design considerations are in place that reduce a majority of the risks or frequency of occurrence. For example, a magnetic clip design to keep the frame standing upright has been incorporated, previously sharp corners in the design have been filleted, and the user can adjust the payload speed through the trolley speed or stand in a location away from the payload swing path.

6.4 Design for Manufacturing

6.4.1 Number of Parts

There are 37 main components, a clip, 2 magnets, timing belt. In total this makes 41 parts.

6.4.2 Number of Threaded Fasteners

There are 40 total fasteners: 8 to attach the hinges and 32 for the aluminum extrusion.

6.4.3 Theoretically Necessary Components

- Trolley
- Rails (Serves as a support for the trolley to rest on top of and move across)
- Timing Belt
- Stepper Motor (Physically drives the timing belt, which moves the entire trolley)
- Arduino Leonardo (Is an essential control system component that directs the parts)
- Control Switch
- Support Legs (Supports the entire structure)
- Payload / Rope

In previous iterations, the design was much closer to the minimum number of parts. In the current trolley, it is split into the holders, spools, and trolley, but before, there were all 1 solid trolley piece. The reason it was split into multiple components was that if the trolley was printed as a singular piece, the complex geometries would have made the 3D print time much longer, and there would be more required support material. A potential change to get closer to the minimum components would be to change the A-frame support leg to simply 2 legs like an upside down V shape (remove the support bar). However, this comes at the cost of weakening the structure as a whole and reducing the amount of weight it can support.

6.5 Design for Usability

6.5.1 Vision Impairment

A vision impairment may affect how a user perceives the motion of the trolley and payload across the track. The design of the product, however, is mostly through silver / black colors with the aluminum frames and CAD parts respectively. In addition, the tennis ball payload still has its bright neon green color, which makes it easily visible Therefore, there shouldn't be much issue in differentiating each individual portion of the device. Such as the case with the contrast in colors for the aluminum track and darker trolley.

6.5.2 Hearing Impairment

A hearing impairment should have absolutely no effect towards the functionality of the device. Since the trolley is motor controlled and can be manually adjusted, there should be no factors in which a hearing defect can affect. However, there is a slight ringing noise when the stepper motor is activated on very low rotational speeds. If the user's hearing is sensitive enough, the excess ringing noise can have an effect on them. But in most cases, the motor would never be adjusted to such low speeds.

6.5.3 Physical Impairment

Physical impairments can have a effect on the device. This aspect would be most likely occurring with the device's transportation phase. Although the device only weighs approximately 9 pounds, the user can potentially struggle with carrying its meter-long structure and possibly its weight if they have muscle weakness. Users with arthritis in their hands may have some issues when unclipping the leg frames and adjusting the spool reel for the payload.

6.5.4 Control Impairment

Some fine motor control is necessary in order to fold the device's legs in and out, as well as to plug in the power to the Arduino and push the buttons on the controller. Users who are highly impaired might not properly balance the machine when setting it up, or might accidentally push both buttons at the same time. However in general due to the simple two button control scheme and general robustness of the system, only very serious control impairment should pose an issue.

7 Final Prototype

7.1 Overview

The Jolley Trolley reached a final prototype after some features were added on and revised. Regarding the performance goals, it reached a top speed of .933 ft/s, had soft stops that prevented it from moving once it reached the end, and ended up weighing approximately 9.8 pounds. As such, the Jolley Trolley accomplished 2/3 Performance goals with the goal of speed being very close to accomplished. A CAD rendition of the Jolley Trolley System is seen below in Fig.33.

Figure 33: CAD of Final Prototype. a) Side view b) Front view c) Top view d) Isometric view

A final version of the Jolley Trolley can be seen below in Fig. 34.

Figure 34: The Final Jolley Trolley in all its Glory

7.2 Performance Goal Assessment

7.2.1 Performance Goal: Speed

The speed was controlled with an Arduino microcontroller which sent a step signal to a stepper controller which caused the motor to step. The stepping rate affected the actual speed of the trolley, and was implemented in the program according to the analytical methods described before. When we actually tested the trolley in real life, the maximum speed was 0.933ft/s, just shy of our goal of 1ft/s. The reason for this is most likely that the stepper motor was not getting enough power, despite the stepper controller being set to deliver the maximum amount of power possible. This could be mitigated in the future using a higher powered motor with a corresponding controller.

7.2.2 Performance Goal: Soft Stop

The Jolley Trolley has a soft stop system that relies of hall effect sensors on each end of the tracks. When the 2 magnets attached to the trolley move towards the ends of each rail, the hall effect sensors detect the magnet's magnetic field and tells the Arduino to stop the stepper motor. These hall effect sensors are shown in Fig. 35

Figure 35: Hall Effect Sensor

7.2.3 Performance Goal: Weight

The design specifications of the Jolley Trolley limits the weight to less than 10 pounds. Thus, after the device was fully built and weighted, the ensuing number turned out to be approximately 9.8 pounds. Although it met the requirements, a way in which the weight can be optimized and lowered can be through topological optimization and further reducing any unnecessary material volume from the 3D printed parts.

7.3 Features

In addition to the Performance Goals, the Jolley Trolley was created with a few extra features in mind. These features are intended to improve the usability of the Jolley Trolley and makes for good design choices overall.

7.3.1 Storage Clips

Storage clips were 3D printed and attached to the sidebars connected between the leg frames. Both sidebars had two clips to attach to the upper aluminum tracks. These clips served the purpose of securing the loosened leg frames onto the tracks when the device is folded. Nevertheless, the curved grooves on the clips help bypass the middle indentation on the aluminum bars. The clips can be observed on the image below.

Figure 36: CAD of Storage Clips

The image below shows the clips when clipped onto the top rail in a folded position.

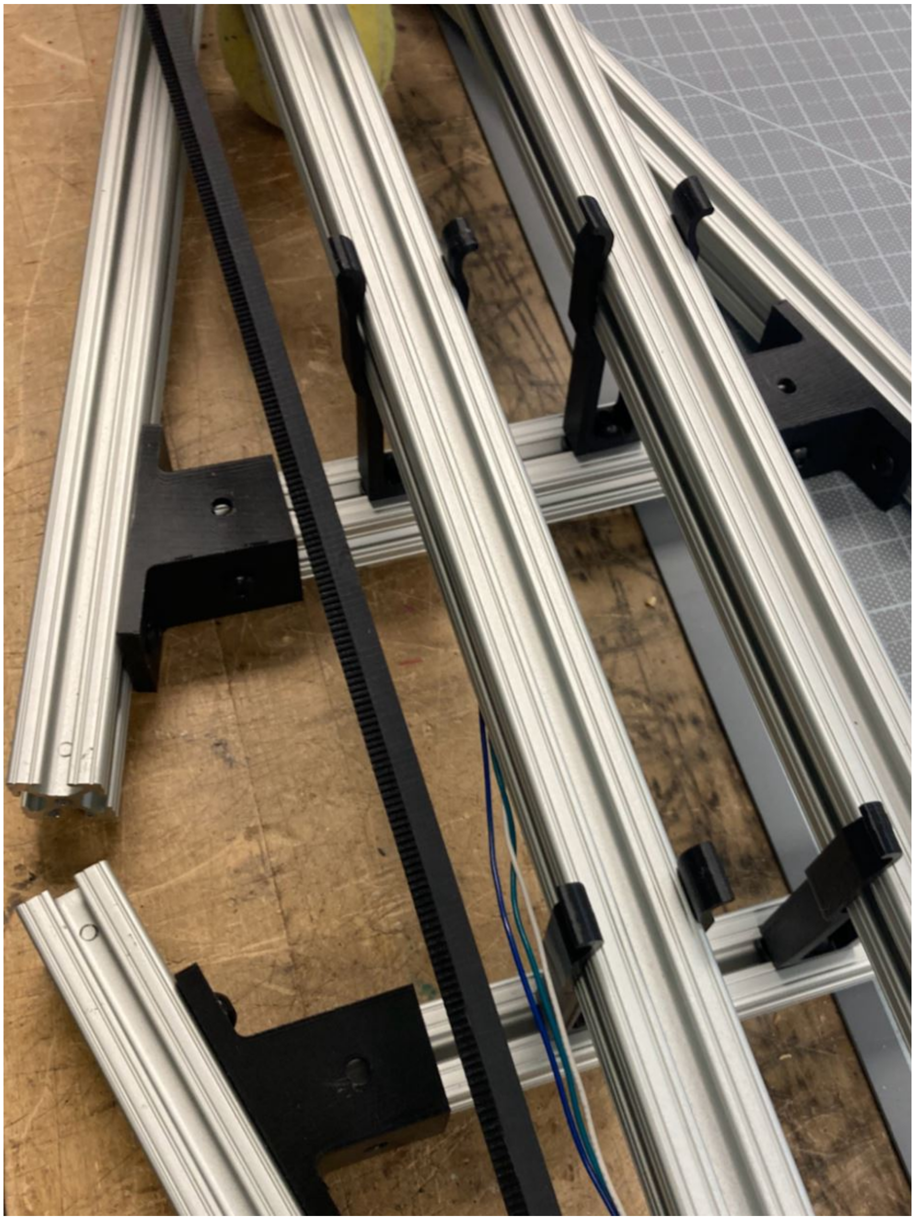


Figure 37: Storage Clips in Closed Position

7.3.2 Winch

On top of the trolley, a winch system was designed to help adjust the length of the cable. This is seen in Fig. 38.

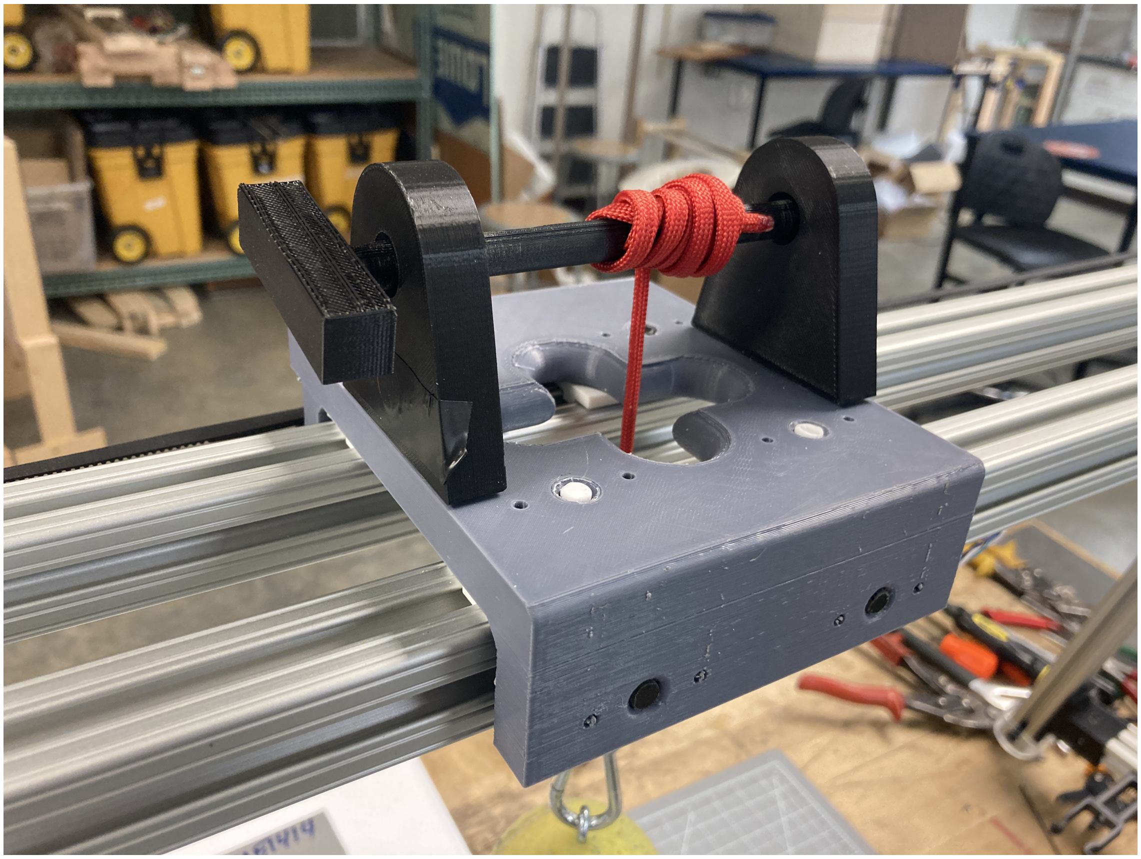


Figure 38: Jolley Trolley Winch System

This cable is attached to a payload through a carabiner clip and if necessary the payload can be changed from a green tennis ball to anything else that can be attached. The winch system itself consists of a 4 3D printed parts: 2 mounting brackets with magnets glued on to them and a twisting spool split into 2 parts. The two magnets are intended to interface with the hall effect sensors. The mount is press fitted onto the trolley and the spool is split into different sections, as illustrated below in Fig. 39

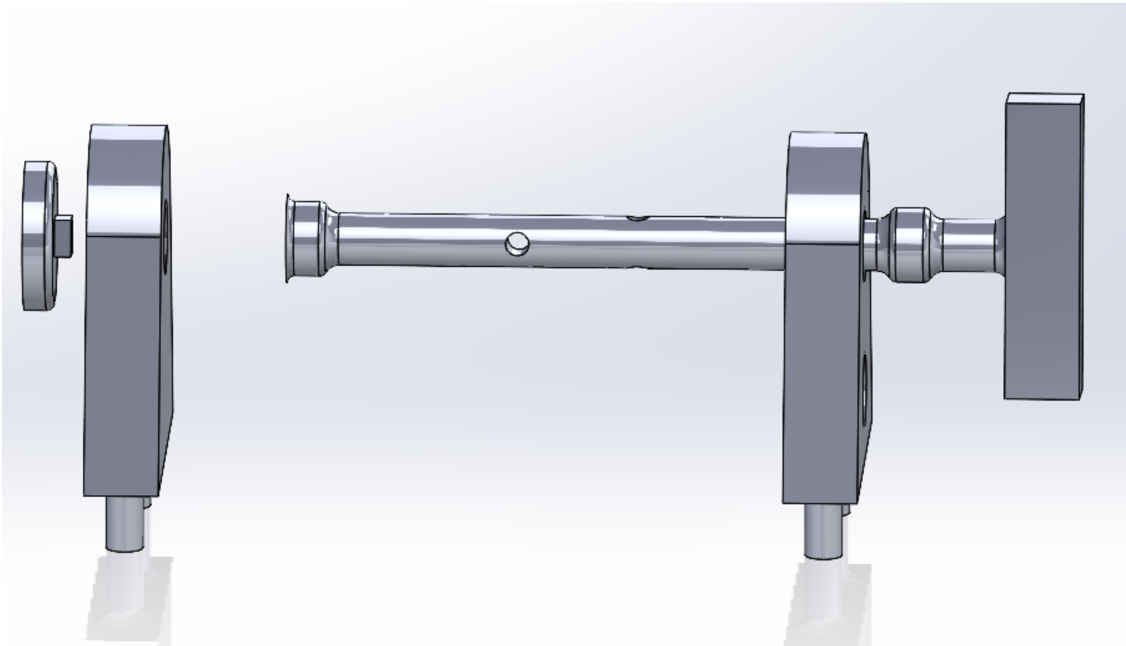


Figure 39: Exploded Winch View

When the cable length needs to be changed, the spool is pressed inwards, releasing the spool to freely spin. After adjusting to the desired length, the spool is lightly pressed back into the mount and secured as a pseudo press fit.

7.3.3 Wire Routing

In order to keep the wires out of the way during operation, we soldered our own custom Arduino shield to hold all the circuitry that went to the Arduino and stepper controller. This can be seen in Fig. 40.

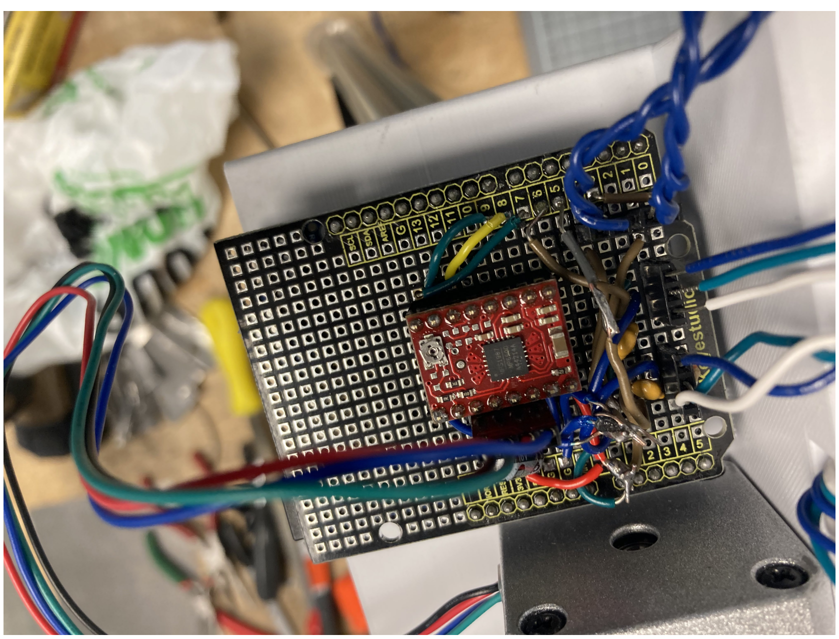


Figure 40: Close up of arduino (with shield)

Then the only wires that needed to be plugged in were the wires for the stepper motor, control switches, and hall effect sensors. The hall effect sensors were mounted in grooves that were designed in our 3D printed parts. The control switch scheme was very simple, with one button to go right and the other to go left. The Arduino would read in the desired direction from the switch, check to make sure that the hall effect sensor corresponding to that direction was not triggered, and if not, tell the stepper motor to keep stepping.

7.3.4 Pulley - Trolley Plate

To elaborate on the Pulley system, a timing belt connects a stepper motor on one end of the rails, the trolley, and another pulley on the other end of the rail. On the trolley itself, the timing belt is attached to a removable, 3D printed plate that was press fitted onto the trolley. The timing belt itself can be removed to adjust for tension or to be replacement. This is seen in Fig. 41 .

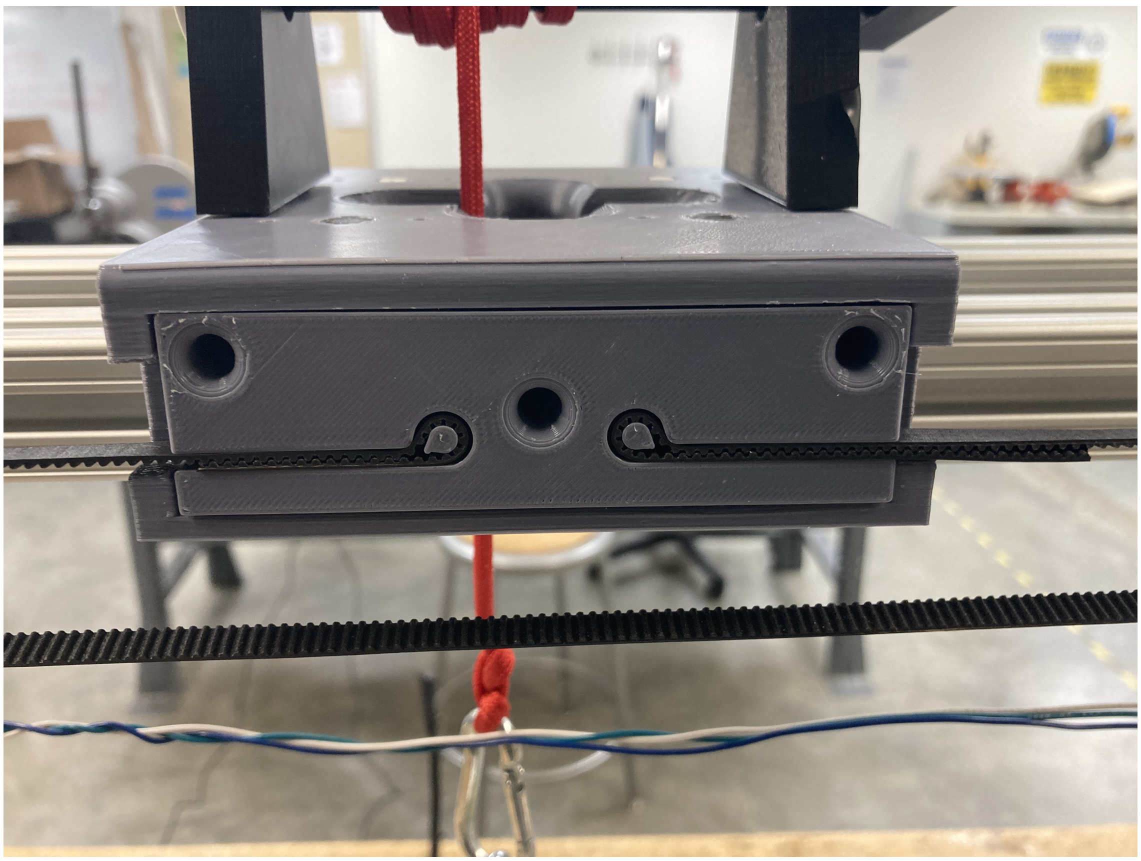


Figure 41: Close-Up of Timing Belt Plate on Trolley

7.3.5 Feet Support

Rubber end caps were ordered and screwed onto the bottom of the aluminum leg frames in order to reinforce stability of the device when held in a standing position. Although the caps grounded the frame feet securely, the feet is angled slightly, and not completely set in place. Further modifications would be required to fully cover and set the feet in place.

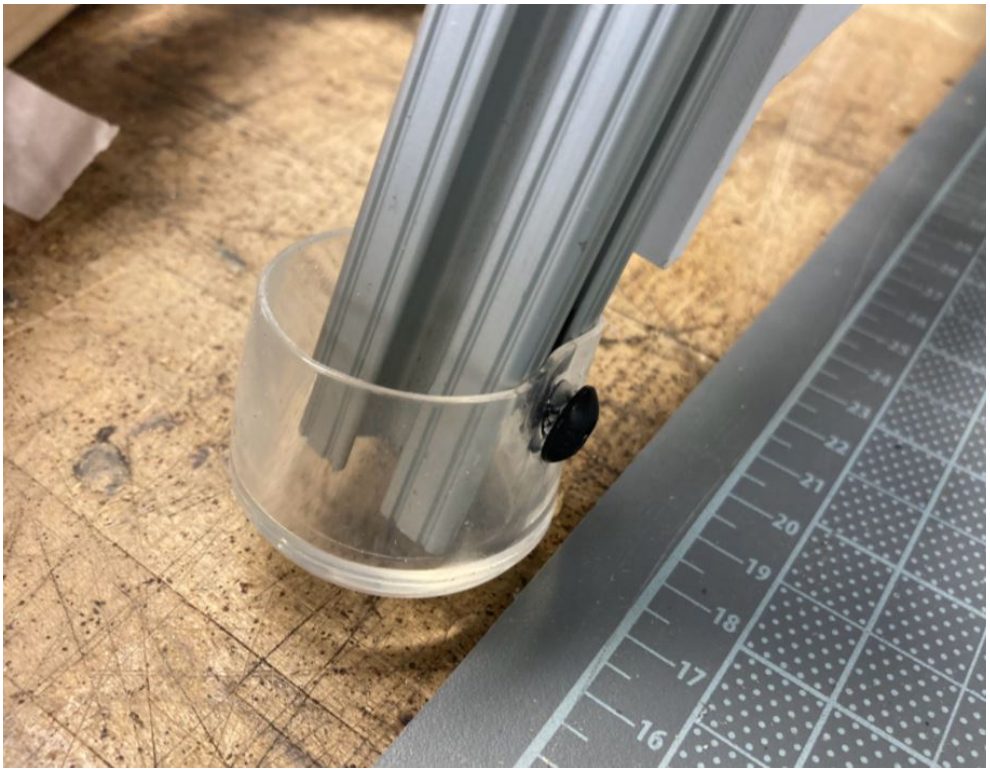


Figure 42: Feet Support

7.4 Improvements for the Future

In order to improve our design, we would recommend a variety of modifications. First, a higher power motor and controller would allow the trolley speed to be increased. Next, we recommend a carrying case or duffel bag of some sort to move the trolley from place to place, because while the current device is light and sturdy during transit, it isn't particularly wieldly. We would also recommend 3D printing some custom feet caps that will sit flat on the ground, rather than the current rubber ones that sit at an angle. Additionally, integrating the current Jolley Trolley with a joystick controller would mean it could be controlled in a more intuitive way. Finally, designing a mechanism to lock the system in place when it is upright would also add some stability and peace of mind to the operation. All in all, despite these many improvements that can be made, we are satisfied with the production quality of our current prototype.

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A Software Code - Arduino

```
// PINS ----------------------------------
const int stepPin = 9;
const int dirPin = 7;
const int sleepPin = 8;
const int rightSwitchPin = 3;
const int leftSwitchPin = 4;
const int rightHallPin = 5;
const int leftHallPin = 6;

// SETTINGS ----------------------------------
const float vMax = 1.15; // [ft/s] maximum trolley speed along bridge
const float a = 1; //[f/s/s] acceleration of trolley
const float oneRevSteps = 200;  // stepper motor steps per one revolution
// convert between speed (ft/s) and delay time (us)
float dt(float v){
  return 3.14*(0.083)/(oneRevSteps*v)*1000000;
}
const float dtMax = dt(vMax);
// generate new speed based on constant acceleration
float vNew(float vCurr, float vDes){
  if (vCurr == vDes){
    return vCurr;
  }
  else{
    if(vDes - vCurr > 0){
      return dt(vCurr)*a + vCurr;
    }
    else{
      return vCurr - dt(vCurr)*a;
    }

  }
}
const float dtBase = dt(vMax);
float dtCurrent = dtBase;


// UTILITIES ----------------------------------
//from Dr. P
void DelayMicroSec(long dt_delay) {
  float t_start = micros();
  while (dt_delay - (micros() - t_start) > 10000) {
    delayMicroseconds(5000);
  }
  delayMicroseconds(dt_delay - (micros() - t_start));
}

void ramp_up(int finalSpeed, int ΔT){
  ;
}


// MOTORS ----------------------------------
void turn_on_motors(){
```

```
  digitalWrite(sleepPin,HIGH);
  Serial.println("Motors on.");
}

void turn_off_motors(){
  digitalWrite(sleepPin,LOW);
  Serial.println("Motors off.");
}

//This function is a bit over complicated. Essentially it was going to add in acceleration by
//calculating the next time step based on a speed from v = vo + a*Dt, with a constant acceleration
//or deceleration. But I never finished writing it so it just always moves at the max speed.
float move_motor_speed(float vDes, float vCurr, int moveDir){
  // updating direction
  if (moveDir == 1){
    digitalWrite(dirPin, LOW);
  }
  else {
    digitalWrite(dirPin, HIGH);
  }

  // checking if it needs to stop
  if(moveDir == 1){
    if(!digitalRead(rightHallPin)){
      return;
    }
    else if(digitalRead(rightSwitchPin)){
      return;
    }
  }
  else{
    if(!digitalRead(leftHallPin)){
      return;
    }
    else if(digitalRead(leftSwitchPin)){
       return;
    }
  }
  Serial.println("ready to move");
  // move with speed/acceleration

  vCurr = vNew(vCurr,vDes);
  dtCurrent = dt(vCurr);

  digitalWrite(stepPin, HIGH);
  DelayMicroSec(dtMax/2);
  digitalWrite(stepPin, LOW);
  DelayMicroSec(dtMax/2);

  return vCurr;
}
```

```
// SETUP ------------------------------------
void setup() {
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
  pinMode(sleepPin, OUTPUT);
  pinMode(rightSwitchPin, INPUT_PULLUP);
  pinMode(leftSwitchPin, INPUT_PULLUP);
  pinMode(rightHallPin, INPUT_PULLUP);
  pinMode(leftHallPin, INPUT_PULLUP);

  Serial.begin(9600);
  delay(50);
}

bool rightSwitchState = false;
bool leftSwitchState = false;
bool rightHallState = false;
bool leftHallState = false;

bool rightSwitchStatePrev = false;
bool leftSwitchStatePrev = false;
bool rightHallStatePrev = false;
bool leftHallStatePrev = false;


// LOOP -------------------------------------
void loop() {

  //currentTime = millis(); //was going to use a Δ time loop but it wasn't ...
     really needed

  rightSwitchState = !digitalRead(rightSwitchPin);
  leftSwitchState = !digitalRead(leftSwitchPin);
  rightHallState = !digitalRead(rightHallPin);
  leftHallState = !digitalRead(leftHallPin);

  turn_on_motors();
  if(rightSwitchState && leftSwitchState){
    Serial.println("Both directions pressed!");
  }
  else if(rightSwitchState){
    float vCurr = 0.0;
    Serial.println("trying to move right");
    if(!rightHallState){
      Serial.println("Moving right");
      vCurr = move_motor_speed(vMax,vCurr,1);

    }
    else{
      Serial.println("At right edge");
    }
  }
  else if(leftSwitchState){
    Serial.println("trying to move left");
```

```
    float vCurr = 0.0;

    if(!leftHallState){

      Serial.println("Moving left");
      vCurr = move_motor_speed(vMax,vCurr,-1);

    }
    else{
      Serial.println("At left edge");
    }
  }
  else{
    Serial.println("<><><>");
  }
  if(rightHallState) Serial.println("RIGHT HALL");
  if(leftHallState) Serial.println("LEFT HALL");

}
```